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author: T. Y. Richard Lee, Ph D

date: November 1980

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CIVIL ENGINEERING LABORATORY
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Port Hueneme, California 93043

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INTRODUCTION

The importance of cogeneration has been greatly emphasized as the cost of energy has increased. The cost of purchased electrical power has, of course, risen with fuel prices. The increases in investment cost for power-producing equipment have forced utility companies to develop new rate structures which emphasize the reduction of reserve capacity by severely penalizing peak usage. All this has resulted in careful reviews of internal power-generating capabilities.

Currently, the U.S. Navy has approximately 12 operational steam-electric power plants with extraction turbines. They are operating in parallel with the utility company serving the area. These plants are representative of numerous small industrial turbine facilities that are capable of practicing cogeneration. A major concern in the cogenerating power plant has been that the operation of the extraction steam turbine electric plants, generally based on operator's judgments, may fail to achieve maximum economy in power usage at Naval installations. At some arbitrary control settings, or in response to a demand level at which peak shaving is initiated, some electrical power for the activity is "bought" from a utility company and some power is "made" onsite. This combination of purchased versus self-generated power may not result in the least cost power mix as power demand and steam loads vary.

The need for a means of determining the optimum economic mix of self-generated and purchased power in a plant that cogenerates steam and electricity has long been recognized by the U.S. Navy. In view of the possible near-term benefits which can be derived, the Civil Engineering Laboratory (CEL) was funded to develop a computer program. This computer program will provide the plant operator with a method of rapid determination of the optimum make/buy operating decisions for the Navy's existing automatic extraction steam turbine/generator cogenerating plants. The objectives of the study are to:

1. Select a potential Naval demonstration site (U.S. Naval Submarine Base (SUBASE) at New London, Conn. was selected).

2. Develop an algorithm for determining the cost of self-generated electricity.

3. Formulate the site-specific functions for determining the cost of purchased power.

4. Develop a computer program, based upon the above results, for use on the Texas Instruments TI-59 programmable calculator with printer for determining the most economical mix of self-generated and purchased electricity.

5. Provide user with instruction on the use of the computer program.

Although the computer program presented in the report is developed for the application at SUBASE, New London, Conn., it can be modified according to site-specific information, such as the system characteristics and utility rate structure, for the application at other Navy activities with installed steam turbine/generator equipment.

The assistance and cooperation of personnel at the Public Works Office at SUBASE, New London, Conn. is greatly appreciated, particularly that of CDR James C. Hay, LCDR Alan H. Burkett, and Mr. Max C. Browning. Special recognition is given to LCDR Alan Burkett, CEC, USN, for his assistance in optimizing the computer programs for both user convenience and run speed.

SYSTEM DESCRIPTION

The cogeneration system at SUBASE, New London, Conn. is depicted in Figure 1. It consists of four high-pressure steam-generating boilers and three turbine generators. All of the boilers, each rated at 76,500 pounds of steam per hour, are fueled with No. 6 oil and supply steam to 600-psig headers which are interconnected by crossties. Steam in the 600-psig header is usually heated to about 700°F. Boiler no. 1S is a newer boiler than the other three. The overall efficiency of these boilers is assumed to be 72%. The makeup for all heat balances is assumed to lie between 17 and 19% of steam generated by the boilers, and 3% of this is assumed to be blowdown. The majority of the losses represented by the difference between the makeup and the blowdown is assumed to be lost in the export system.

All three turbines are condensing units with automatic extraction. Manufacture information for the turbine/generator sets is listed in Table 1. Turbines no. 3 (TG3) and no. 5 (TG5) receive throttle steam of 600 psi, 700°F from the boilers and both extract 200-psig, 500°F steam for the header to turbine no. 4 (TG4), to the steam-driven power plant auxiliaries, and to the 200-psig export supply. The 5-psig steam is supplied by the bleed from the 5-psig extraction ports of turbines no. 3 and no. 4. A pressure-reducing valve (PRV) and a desuperheater (DSPH) station are piped between the 600- and 200-psig headers for the direct-pressure reduction purpose. There is normally sufficient extraction steam capacity in the turbines so that the PRV can remain closed. If, for any reason, the steam pressure in the 200-psig header drops below the limit, the PRV will open to maintain the header pressure. Performance curves for the three turbines are shown in Figures 2 to 4 from which the overall turbogenerator efficiencies are estimated and listed in Table 1.

The self-generated power onsite and the purchased power from the Groton City Utility Company are connected in parallel to supply the switchgear in the power plant.

SELF-GENERATION ANALYSIS

The algorithms to be employed to calculate the cost of electrical power generated by the cogenerators onsite are presented in this section.

Considering each turbine/generator set shown in Figure 1 as a control volume, equations which represent the conservations of mass and energy principles can be written as follows:

Continuity equation:

For TG3: $$M_{3T} = M_{3H} + M_{3L} + M_{3E} \tag{1}$$

For TG4: $$M_{4T} = M_{4L} + M_{4E} \tag{2}$$

For TG5: $$M_{5T} = M_{5H} + M_{5E} \tag{3}$$

First law of thermodynamics:

For TG3: $$\frac{W_3 \times 3413}{E_{3T}} = (M_{3T} \times H_{3T}) - (M_{3H} \times H_{3H}) - (M_{3L} \times H_{3L}) - (M_{3E} \times H_{3E}) \tag{4}$$

For TG4: $$\frac{W_4 \times 3413}{E_{4T}} = (M_{4T} \times H_{4T}) - (M_{4L} \times H_{4L}) - (M_{4E} \times H_{4E}) \tag{5}$$

For TG5: $$\frac{W_5 \times 3413}{E_{5T}} = (M_{5T} \times H_{5T}) - (M_{5H} \times H_{5H}) - (M_{5E} \times H_{5E}) \tag{6}$$

The explanation of the symbols used in the above-mentioned equations and in Figure 1 is presented in the Nomenclature List.

Combining these equations gives:

$$\begin{aligned}\left(\frac{W_3}{E_{3T}} + \frac{W_4}{E_{4T}} + \frac{W_5}{E_{5T}}\right)3413 = {} & (M_{3H} + M_{3L} + M_{3E})\, H_{3T} + (M_{4L} + M_{4E})\, H_{4T} \\ & + (M_{5H} + M_{5E})\, H_{5T} - (M_{3H} \times H_{3H}) \\ & - (M_{3L} \times H_{3L}) - (M_{3E} \times H_{3E}) \\ & - (M_{4L} \times H_{4L}) - (M_{4E} \times H_{4E}) \\ & - (M_{5H} \times H_{5H}) - (M_{5E} \times H_{5E}) \end{aligned} \tag{7}$$

Assuming that the piping losses are negligible, then

$$H_{3T} = H_{5T} = H_S \tag{8}$$

$$H_{3H} = H_{5H} = H_{4T} = H_H \tag{9}$$

$$H_{3L} = H_{4L} = H_L \tag{10}$$

Substitution of these relations along with the following identities

$$M_{4L} (H_H - H_L) = M_{4L} (H_S - H_L) - M_{4L} (H_S - H_H)$$

and

$$M_{4E} (H_H - H_{4E}) = M_{4E} (H_S - H_{4E}) - M_{4E} (H_S - H_H)$$

into Equation (7) yields:

$$\begin{aligned}\left(\frac{W_3}{E_{3T}} + \frac{W_4}{E_{4T}} + \frac{W_5}{E_{5T}}\right)3413 = {} & (M_{3H} + M_{5H} - M_{4T})(H_S - H_H) \\ & + (M_{3L} + M_{4L})(H_S - H_L) \\ & + M_{3E}(H_S - H_{3E}) + M_{4E}(H_S - H_{4E}) \\ & + M_{5E}(H_S - H_{5E})\end{aligned} \tag{11}$$

From the heat balance of this system, it has been found* that the quantity of the 5-psig steam, to be supplied to the deaerator, is about the same as that to be exhausted from the three steam-driven auxiliaries as shown in Figure 1. Therefore, it is reasonable to assume that M_{3L} + M_{4L} is equal to M_L, the low-pressure export steam.

Assume that the amount of steam consumed for steam-driven auxiliaries between the 200-psig and the 5-psig headers is negligible compared with high-pressure export steam M_H. The term $(M_{3H} + M_{5H} - M_{4T})$ in Equation 11 will be equal to the high-pressure export steam supply M_H. In addition, it is reasonable to assume that

*Carlson & Sweatt Engineers. "Report on economics of electrical power generation," New York, N.Y., Aug 1972. (Prepared for Naval Submarine Base, New London, Conn.)

$$H_S - H_{3E} \div H_S - H_{4E} \div H_S - H_{5E}$$

With the above-mentioned assumptions, Equation 11 can be rewritten as

$$\left(\frac{W_3}{E_{3T}} + \frac{W_4}{E_{4T}} + \frac{W_5}{E_{5T}} \right) 3413 = M_H (H_S - H_H) + M_L (H_S - H_L)$$

$$+ (M_{3E} + M_{4E} + M_{5E}) (H_S - H_E) \qquad (12)$$

Where H_E is defined as the enthalpy of the mixed exhaust steam, and $M_{3E} + M_{4E} + M_{5E}$ is the total condensing steam flow of this system with the limit value of $M_{3M} + M_{4M} + M_{5M}$.

Up to this point, Equation 12 has been derived for the total thermal energy to be converted into the predetermined electrical power, $W_3 + W_4 + W_5$, while meeting the steam load demand at any given time.

In order to compute the cost for the electricity generated onsite, the turbine heat rate (T_{HR}) is determined and used as follows:

Total energy added to turbines:

$$(M_{3T} + M_{4T}) H_S$$

The thermal energy which is recoverable from the turbine system:

$$M_H \times H_H + M_L \times H_L + (M_{3E} + M_{4E} + M_{5E}) \times H_C$$

Where H_C is the average enthalpy value of the condensate from turbines.

The turbine heat rate (T_{HR}) is the net heat input to the turbines per unit of electrical generated, which can be written as:

$$T_{HR} = [(M_{3T} + M_{5T}) H_S - (M_H \times H_H) - (M_L \times H_L)$$

$$- (M_{3E} + M_{4E} + M_{5E}) H_C]/(W_3 + W_4 + W_5) \qquad (13)$$

Substitution of Equation (12) into Equation (13) leads to

$$
\begin{aligned}
T_{HR} = \; & \{[(W_3/E_{3T}) + (W_4/E_{4T}) + (W_5/E_{5T})]\; 3413 \\
& + (M_{3E} + M_{4E} + M_{5E})\;(H_E - H_C)\} \div (W_3 \\
& + W_4 + W_5)
\end{aligned}
\tag{14}
$$

Where the turbine heat rate, T_{HR}, in unit of Btu per kW-hr, is the instantaneous heat rate derived from a particular heat balance of the overall cogenerating system at a fixed-load situation.

Examination of Equation 14 indicates that it will be more efficient to generate electricity onsite when the system is operating at the minimum allowable condensing level, i.e., when $(M_{3E} + M_{4E} + M_{5E})$ is minimum. It is, therefore, the objective of this study to seek an optimal balance between the power demand set point and the operation of the three condensing turbines.

With the information available for the heating value of fuel, fuel price and boiler efficiency, the cost of self-generation of W_T (= W_3 + W_4 + W_5) electrical power at any expected export steam loads, M_H and M_L can be expressed as follows:

Unit cost of self-generation, ¢/kW-hr is

$$C_{US} = T_{HR} \times P_F/(H_V \times E_B) \tag{15}$$

Total cost of self-generated electricity, $W_3 + W_4 + W_5$, over the time period of T hours (which may be a period of one shift or less) is

$$C_{TS} = C_{US} \times (W_3 + W_4 + W_5) \times T \tag{16}$$

PURCHASED POWER ANALYSIS

The SUBASE at New London, Conn. purchases part of its electrical power from the Department of Utilities of the City of Groton. The rate structure, presented in Table 2, includes two charges during the 30-day billing period: the demand charge and the energy charge. The energy charge is simply a predetermined price per kW-hr used. The price can vary with the amount purchased, but basically it is a straightforward cost. The demand charge is currently established as a predetermined price times the highest peak value created over the last 11 months. The demand charge represents a very significant part (about 25%) of the total utility bill. In such a structure, the demand charge becomes almost like a fixed cost, which has to be paid whether it is utilized or not. Each bill for the current month will be increased or decreased by an amount equal to the fuel adjustment factor (F_A) times the total energy (kW-hr) used in the current billing month.

The cost of the purchased electricity over the time period, T, during the billing month is calculated according to the rate structure listed in Table 2 as follows

(i) The demand charge, \$/kW-hr:

$$4.72/(30 \times 24)$$

(ii) The energy charge, \$:

$$(0.0343 + F_A)\ R_1 + (0.0269 + F_A)\ R_2 + (0.0211 + F_A)\ R_3$$

The values of coefficients R_1, R_2 and R_3 are dependent upon the values of the cumulative energy consumption at the beginning (K_1), and that at the end (K_2) of the time period, T. The relation between K_1 and K_2 can be presented as

$$K_2 - K_1 = K_P \times T$$

Where K_P represents the electrical power to be purchased during time period, T, from the utility company.

These coefficients R_1, R_2 and R_3 are to be determined according to the following conditions:

(1) $K_2 < 50{,}000$

$R_1 = K_P \times T$

$R_2 = R_3 = 0$

(2) $50{,}000 < K_2 < 300 \times D_U$

(a) $K_1 < 50{,}000$

$R_1 = 50{,}000 - K_1$

$R_2 = K_2 - 50{,}000$

$R_3 = 0$

(b) $K_1 > 50{,}000$

$R_2 = K_P \times T$

$R_1 = R_3 = 0$

(3) $300 \times D_U < K_2$

(a) $K_1 < 50{,}000$

$R_1 = 50{,}000 - K_1$

$R_2 = 300 \times D_U - 50{,}000$

$R_3 = K_2 - 300 \times D_U$

(b) $50{,}000 < K_1 < 300 \times D_U$

$R_1 = 0$

$R_2 = 300 \times D_U - K_1$

$R_3 = K_2 - 300 \times D_U$

(c) $300 \times D_U < K_1$

$R_1 = R_2 = 0$

$R_3 = K_P \times T$

Thus, the total cost (C_{TP} in dollars) for the purchased utility (K_P) over the period, T, is

$$C_{TP} = (0.0343 + F_A) R_1 + (0.0269 + F_A) R_2 + (0.0211 + F_A) R_3 + [4.72/(30 \times 24)] \times D_U \times T \quad (17)$$

And the unit cost of utility (C_{UP} in ¢/kW-hr) for the purchased power (K_P) is

$$C_{UP} = [C_{TP}/(K_P \times T)] \times 100 \quad (18)$$

OPTIMUM MAKE/BUY DECISION ANALYSIS

When there is a combination of self-generation and purchase of electrical power, the total unit cost (in cents per kW-hr) can be expressed as:

$$C_U = \frac{C_{TS} + C_{TP}}{D \times T} \quad (19)$$

Where C_{TS} and C_{TP}, the total costs of self-generation and purchase power, respectively, have been derived in the preceding sections. It is evident from Equations 16 and 17 that at the specified demands of power and steam, both C_{TS} and C_{TP} are a function of the total self-generation onsite, W_T (= $W_3 + W_4 + W_5$). Thus, Equation 19 can be written mathematically as:

$$C_U (W_T) = C_{TS}(W_T) + C_{TP} (W_T) \quad (19\text{-}1)$$

A realistic problem of this combination, Make versus Buy, which has been encountered by plant operators, is how much power ought to be generated onsite in order to meet the requirements at the lowest cost. In order to solve this optimization problem, which is the objective of this study, it is necessary to select the optimum value of self-generation, W_T, to minimize the total unit cost derived from Equation 19. A necessary condition for a minimum value of C_U to exist is that:

$$\frac{dC_U\ (W_T)}{dW_T} = 0 \qquad (19\text{-}2)$$

This is done here numerically, using a hand-held programmable calculator, in accordance with the following operational limits for the system:

- Maximum extraction flow for each steam turbine
- Minimum condensing flow for each steam turbine
- Limits for turbine/generator power output

It should be noted that the solution of C_U determined from Equation 19 may not be minimum where Equation 19-2 holds, but an optimum one with which the above-mentioned constraints comply.

The numerical procedure for determining the optimum value of unit cost, C_U, starts with the assumption that maximum possible electrical power will be generated onsite and any additional electricity will be purchased in order to meet the power demand requirement over the time period, T. The resultant unit cost, C_U, is then compared with the new value resulting from the assumption of reducing the self-generation capacity by a predetermined decrement and the increasing purchased electrical power. This iteration is continued, i.e., the assumption of generating less electricity onsite and purchasing more from the utility, until the optimum (or minimum) value of unit cost C_U is found.

COMPUTER PROGRAMS

Program Description

The computer programs are developed according to the analysis presented in the previous section and are designed for use on a Texas Instruments TI-59 programmable calculator with a PC-100C printer. The program can be utilized by the operators of the power plant at any time to determine the optimum mix of self-generated and purchased electrical power at SUBASE, New London, Conn. The results of this program will provide a guideline which will enable the operators to operate the power plant in the most economical way.

A flow chart describing the logic of the computer program is shown in Figure 5. The listing of the computer program suitable for use on the Texas Instruments TI-59 programmable printing calculator appears in Table 3. The first two columns of the program listed in Table 3 are for the program location and key code, respectively. The group of three digits shows the location in program memory of each instruction. This not only allows the user to keep track of instructions, but also tells the calculator the order in which to complete the instructions. Since the calculator can only understand numbers, each key symbol on the keyboard is assigned a two-digit code number known as a key code corresponding to the instruction stored in the program memory location.

There are two groups of information required for this program to run. The first group of information is the characteristics of the onsite generating system which can be named "System Information" including the efficiencies of turbine/generator sets and boilers, the thermodynamic properties at the points of interest, and the constraints of the turbine/generator sets. All the systems' information is treated as constants and is stored at data registers 0 to 17. These values are listed in Table 4. If any change is necessary due to equipment modifications, it is relatively easy to revise the required values with a basic understanding of programming on the TI-59 calculator. It is worthwhile to mention that the constraints of the turbine/generator sets are stored with the assumption that all three sets are on-line for operation. However, the user still has the options to make his choice of any other combination of turbine/generator sets in the process of determining the optimum mix of self-generated and purchased electrical power. To assume putting an out-of-service turbine/generator set back in service, the user has to take some simple steps to restore into the data registers the constraints of the equipment before the user starts to run the program. Details of this procedure will be described later.

The second group of information, called "Operat   al Information," consists of ten variables. These all have to be keyed into the calculator by the user when the program is run for the first time. For subsequent runs, only those variables which are different from the previous ones need to be keyed in again with the exception that the values of W_3, W_4 and W_5 have to be reentered for every run. The ten variables and their data registers are listed as follows:

- W_3 R_{20}, highest selected electric output (kW) of TG3
- W_4 R_{21}, highest selected electric output (kW) of TG4
- W_5 R_{22}, highest selected electric output (kW) of TG5
- M_H R_{23}, high pressure (200 psig) export steam (lb/hr)
- M_L R_{24}, low pressure (5 psig) export steam (lb/hr)
- D R_{25}, electric demand (kW) during the time period, T
- K_1 R_{26}, cumulative purchased energy (kW-hr) at the beginning of each run
- F_A R_{27}, fuel adjustment factor ($/kW-hr)
- P_F R_{28}, fuel price (¢/gal.)
- T R_{29}, time period of interest (hr) for each run

All these ten inputs are stored automatically by the program into data registers 20 to 29 (R_{20}-R_{29}). The first three inputs are the selected generator outputs of turbine/generator sets, which are normally the rated capacities, with the condition that the total inputs of W_3, W_4 and W_5 at any time must be either equal to or less than the input of electrical demand D.

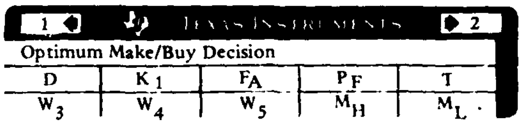
Operating Instructions

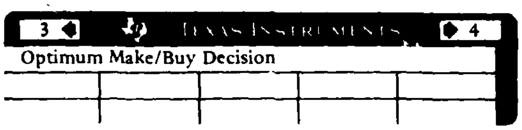
A detailed explanation of how to run this program is presented in this section. A step-by-step user instruction to run the program is shown in Table 5. The explanation of each step is given below.

Step

1 Slide the ON/OFF switches on the TI-59 calculator and the printer to the ON positions. A single zero should be seen in the calculator display.

2 Read magnetic cards. The two magnetic cards used to store the program and the system information are illustrated below.





Each magnetic card is labeled according to the information stored on it. In the upper corners of each card, the number in each space is to indicate the bank numbers recorded on that card. The arrow in each space shows which direction the card must be inserted into the calculator when reading the indicated bank. The space across the center of the card is available for the program title and other pertinent information such as the required partition. Below this line are two rows of boxes. The bottom five boxes are used to indicate the function of the defined keys $\boxed{A}$ through $\boxed{E}$ within the recorded program. The upper row of boxes is used similarly for the keys $\boxed{A'}$ through $\boxed{E'}$.

Step

To read a magnetic card, press $\boxed{\text{CLR}}$ and insert the card into the lower slot on the right side of the calculator. The drive motor of the calculator will automatically pull the card through the calculator. The number of the bank recorded from the entered card is shown in the display after that card side has been read successfully.

Repeat the procedure (Press $\boxed{\text{CLR}}$ and enter a card side) until all four banks (1, 2, 3, and 4) have been correctly read (in any order).

Up to now, the computer program and the system information have been read into the calculator from the magnetic cards and will be stored in the calculator as long as the switches of the calculator and printer are left at "ON" positions continuously.

Step

3 Enter numerical value for W_3 as selected generator output of TG3 and press $\boxed{\text{A}}$. Input will be stored into data register 20 and printed out. The decrement of input for iteration will be in the display after a very short period of computation. (During computation, a "C" appears at the left side of the otherwise blank display.)

4 Enter the value of W_4 and press $\boxed{\text{B}}$. Input will be stored into data register 21 and printed out. The decrement of input will appear in the display after a very short period of computation.

5 Enter the value of W_5 and press $\boxed{\text{C}}$. Input will be stored into data register 22 and printed out. The decrement of input will appear in the display after a very short period of computation.

Step

6 Enter the value of M_H and press $\boxed{D}$. Input in the display is stored into data register 23 and printed out.

7 Enter the value of M_L and press $\boxed{E}$. Input in the display is stored into data register 24 and printed out.

8 Enter the value of D and press $\boxed{2nd}$ $\boxed{A}$. Input in the display is stored into data register 25 and printed out.

9 Enter the value of K_1 and press $\boxed{2nd}$ $\boxed{B}$. Input in the display is stored into data register 26 and printed out.

10 Enter the value of F_A and press $\boxed{2nd}$ $\boxed{C}$. Input in the display is stored into data register 27 and printed out.

11 Enter the value of P_F and press $\boxed{2nd}$ $\boxed{D}$. Input in the display is stored into data register 28 and printed out.

12 Enter the value of T and press $\boxed{2nd}$ $\boxed{E}$. Input in the display is stored into data register 29 and printed out.

Note: If a mistake is made at any above numerical data entering step (3 to 12) simply press $\boxed{CLR}$ and start over again for that step.

13 To run the program, press: $\boxed{RST}$, $\boxed{R/S}$.

When the program is in execution, there is a blinking "C" on the left side of the otherwise blank display. The following results will be printed, successively, for the first and last iterations:

- TG3 electrical output, kW - W_3
- TG4 electrical output, kW - W_4
- TG5 electrical output, kW - W_5
- Total condensing flow, lb/hr - M_C
- Heat rate, Btu/kW-hr - T_{HR}
- Unit cost of self-generation, ¢/kW-hr - C_{US}
- Total cost of self-generation, \$ - C_{TS}
- Unit cost of purchased power, ¢/kW-hr - C_{UP}
- Total cost of purchased power, \$ - C_{TP}
- Total cost, \$ - C_T
- Total unit cost, ¢/kW-hr - C_U

After the last group of output is printed, the display should read "0" indicating that the program has been successfully run and has stopped. A sample printout is given in Table 6. The first outputs are the results calculated using the input values of generator outputs, W_3, W_4, and W_5 given by the user, while the last outputs are the results using the optimum self-generation solutions of W_3, W_4, and W_5.

For repeated or subsequent runs, steps 3, 4, and 5 (for entering the values of W_3, W_4, and W_5) <u>are required to be repeated</u> whether or not the entering values are different from the previous values! However, only those steps from 6 to 12 need to be repeated for which entering values differ from the previous run. The program is then restarted by pressing $\boxed{\text{RST}}$ $\boxed{\text{R/S}}$ after the last value changed.

<u>Caution</u>: If the user has assumed that any one of the turbine/generator sets has been shut down (by entering zeros for W_3, W_4, or W_5) in running the program, he must read bank no. 4 of the magnetic card once again (as described in step 2) in order to restore the system information <u>before</u> he starts to rerun the program for a different combination of turbine/generator sets.

CONCLUSIONS

A computer program designed for use on a hand-held TI-59 calculator, with a PC-100 printer, has been developed to provide the personnel of the power plant at SUBASE, New London, Conn., with a rapid computation of the optimum operating settings for the turbine/generator sets during any given shift. Input parameters of this computer program are left free and, for most of them, are not required to be entered for subsequent runs unless they are different from those previously entered. The most unique feature of this computer program is that it provides the user with maximum flexibility in the choice of the mode of operation of the power plant. This means that all three turbine/generator sets may be assumed online for operation, or any other combinations of one or two turbine/generators may be assumed online in the process of determining the optimum mix of self-generated and purchased electrical power.

The economics of power generation at SUBASE, New London, Conn., has changed quite drastically over the last few years due to the great increase in fuel oil costs. Since purchased power rates have not increased in the same proportion, purchased power has become more economical than onsite power generation. The dramatic influence of the rate structure and fuel price on the total unit cost is evident in Figure 6. The data selected for use in Figure 6 are shown in Table 7. As indicated in Figure 6, it would be more advantageous to the SUBASE to purchase electrical power from the utility than to generate it onsite while the prices of fuel and utilities are increasing at the same rates as before. However, due to the very nature and functioning of the SUBASE, the power supply reliability dictates a reasonable amount of base generation and spinning reserve. Therefore, generation assignments should be made in such a manner as to strike a balance between reliability requirements and economics.

The significance in savings resulting from the optimum operation of the existing cogeneration system at the SUBASE has also been changed over the years. Figure 6 shows that the operation of the power plant at the optimum make/buy ratio in 1972 was not as critical as it became in 1976 and 1979. For example, curve no. 1 illustrates that the optimum operating point in 1972 was at a make/buy ratio 3,500 kW/11,500 kW for a given demand, 15,000 kW. Even when operating 100% off the optimum point, i.e., 7,000 kW/8,000 kW, in 1972 there would have resulted an additional total unit cost of about 0.06 cents per kW-hr. However, a similar deviation from the optimum points (100% off) for curves 2, 3 and 4 would result in additional total unit cost of 0.30, 0.40 and 0.65 cents per kW-hr respectively, the latter of which is typical of 1979. Hence, it can be concluded that more savings would be achieved by operating the existing power plant at, or close to, the determined optimum make/buy decision points as the fuel price is expected to increase continuously.

Figures 7 and 8 present the results of the parametric study of the effect of steam loads and fuel price on total unit cost, respectively. As clearly seen, the variations of steam demand will affect the location of minimum points and the total unit cost levels dramatically. However, the increase of fuel prices may not affect the locations of minimum points but would result in higher additional total unit costs if the plant was not operated at the minimum point.

RECOMMENDATIONS

In order to evaluate the savings resulting from the implementation of this program, a user data sheet is designed and shown in Table 8 for users to record all the relevant information. There are four columns in this user data sheet. The first column records the date and time when the operator starts to use this program. The second column is used to record the operational information. The third column is for the results printed out from the printer. The last column, which is very important for the evaluation, is for the actual information, after the fact, that will be used to calculate the costs to be compared with those in the third column.

Although the computer program developed in this study is for use at SUBASE, New London, Conn., its applicability to other Navy activities which already practice cogeneration with steam turbine/generator equipment is recommended to be investigated by modifying this program according to the site-specific requirements, such as thermodynamic characteristics of the cogeneration system, the utility rate structure and load demands.

Table 1. Steam Turbine/Generator Ratings at SUBASE, New London, Conn.

Turbine/ Generator	Manufacture	Year Installed	Name Plate Capacity (kW)	Maximum Throttle Flow (lb/hr)	Extraction Pressure (psig)	Exhaust Pressure (in.abs)	Overall Efficiency
TG3	GE	1944	3,500	129,000	200 and 5	1.5	0.70
TG4	Elliot	1940	4,000	75,000	5	1.5	0.68
TG5	Terry	1977	5,000	160,000	200	4	0.72

Table 2. Utility Structure at SUBASE, New Longon, Conn. (as of April 1980)

Demand Charge per Month: (with .15 per kW credit)	$4.72/kW
Energy Charge: *(subject to 5% discount)*	
First 50,000 kW-hr	$0.0343/kW-hr
Over 50,000 kW-hr and up to 300 x billing demand	$0.0269/kW-hr
Over 300 x billing demand	$0.0211/kW-hr

Table 3. Listing of Make/Buy Decision Computer Program

000	42	STO
001	01	01
002	51	51
003	76	LBL
004	69	OP
005	43	RCL
006	39	39
007	65	
008	43	RCL
009	39	39
010	95	=
011	92	RTN
012	76	LBL
013	89	π
014	71	SBR
015	69	OP
016	85	+
017	43	RCL
018	26	26
019	75	-
020	43	RCL
021	34	34
022	95	=
023	92	RTN
024	71	SBR
025	69	OP
026	85	+
027	43	RCL
028	26	26
029	76	LBL
030	55	÷
031	75	-
032	05	5
033	00	0
034	00	0
035	00	0
036	00	0
037	95	=
038	92	RTN
039	76	LBL
040	52	EE
041	99	PRT
042	65	×
043	43	RCL
044	17	17
045	65	×
046	05	5
047	95	=
048	92	RTN

049	76	LBL
050	11	A
051	42	STO
052	20	20
053	29	CP
054	22	INV
055	67	EQ
056	00	00
057	62	62
058	42	STO
059	11	11
060	42	STO
061	08	08
062	71	SBR
063	52	EE
064	42	STO
065	30	30
066	92	RTN
067	76	LBL
068	12	B
069	42	STO
070	21	21
071	29	CP
072	22	INV
073	67	EQ
074	00	00
075	80	80
076	42	STO
077	12	12
078	42	STO
079	09	09
080	71	SBR
081	52	EE
082	42	STO
083	31	31
084	92	RTN
085	76	LBL
086	13	C
087	42	STO
088	22	22
089	29	CP
090	22	INV
091	67	EQ
092	00	00
093	98	98
094	42	STO
095	13	13
096	42	STO
097	10	10

Table 3. Continued

```
098   71  SBR
099   52  EE
100   42  STO
101   32   32
102   92  RTN
103   76  LBL
104   14   D
105   42  STO
106   23   23
107   99  PRT
108   92  RTN
109   76  LBL
110   15   E
111   42  STO
112   24   24
113   99  PRT
114   92  RTN
115   76  LBL
116   16  A'
117   42  STO
118   25   25
119   99  PRT
120   92  RTN
121   76  LBL
122   17  B'
123   42  STO
124   26   26
125   99  PRT
126   92  RTN
127   76  LBL
128   18  C'
129   42  STO
130   27   27
131   99  PRT
132   92  RTN
133   76  LBL
134   19  D'
135   42  STO
136   28   28
137   99  PRT
138   92  RTN
139   76  LBL
140   10  E'
141   42  STO
142   29   29
143   99  PRT
144   98  ADV
145   92  RTN
146   06   6
147   69  OP
148   17   17
149   25  CLR
150   92  RTN
151   43  RCL
152   08   08
153   85   +
154   43  RCL
155   09   09
156   85   +
157   43  RCL
158   10   10
159   95   =
160   42  STO
161   18   18
162   43  RCL
163   02   02
164   65   ×
165   43  RCL
166   23   23
167   85   +
168   43  RCL
169   03   03
170   65   ×
171   43  RCL
172   24   24
173   95   =
174   42  STO
175   19   19
176   71  SBR
177   02   02
178   66   66
179   43  RCL
180   33   33
181   67   EQ
182   02   02
183   00   00
184   75   -
185   43  RCL
186   35   35
187   95   =
188   67   EQ
189   02   02
190   63   63
191   94  +/-
192   22  INV
193   77   GE
194   02   02
195   51   51
196   43  RCL
197   33   33
198   42  STO
199   35   35
```

Table 3. Continued

200	43	RCL
201	30	30
202	22	INV
203	44	SUM
204	20	20
205	43	RCL
206	20	20
207	32	X:T
208	43	RCL
209	11	11
210	22	INV
211	77	GE
212	02	02
213	16	16
214	42	STO
215	20	20
216	43	RCL
217	31	31
218	22	INV
219	44	SUM
220	21	21
221	43	RCL
222	21	21
223	32	X:T
224	43	RCL
225	12	12
226	22	INV
227	77	GE
228	02	02
229	32	32
230	42	STO
231	21	21
232	43	RCL
233	32	32
234	22	INV
235	44	SUM
236	22	22
237	43	RCL
238	22	22
239	32	X:T
240	43	RCL
241	13	13
242	22	INV
243	77	GE
244	01	01
245	76	76
246	42	STO
247	22	22
248	61	GTO
249	01	01
250	76	76
251	43	RCL
252	30	30
253	44	SUM
254	20	20
255	43	RCL
256	31	31
257	44	SUM
258	21	21
259	43	RCL
260	32	32
261	44	SUM
262	22	22
263	22	INV
264	86	STF
265	05	05
266	43	RCL
267	20	20
268	85	+
269	43	RCL
270	21	21
271	85	+
272	43	RCL
273	22	22
274	95	=
275	42	STO
276	33	33
277	75	-
278	43	RCL
279	25	25
280	95	=
281	94	+/-
282	42	STO
283	39	39
284	29	CP
285	77	GE
286	02	02
287	91	91
288	00	0
289	42	STO
290	39	39
291	43	RCL
292	20	20
293	55	÷
294	43	RCL
295	05	05
296	85	+
297	43	RCL
298	21	21
299	55	÷
300	43	RCL
301	06	06

Table 3. Continued

302	85	+
303	43	RCL
304	22	22
305	55	÷
306	43	RCL
307	07	07
308	95	=
309	65	×
310	43	RCL
311	15	15
312	95	=
313	42	STD
314	34	34
315	75	-
316	43	RCL
317	19	19
318	95	=
319	55	÷
320	43	RCL
321	01	01
322	95	=
323	32	X:T
324	04	4
325	69	DP
326	17	17
327	43	RCL
328	18	18
329	77	GE
330	03	03
331	33	33
332	32	X:T
333	42	STD
334	36	36
335	65	×
336	43	RCL
337	04	04
338	85	+
339	43	RCL
340	34	34
341	95	=
342	55	÷
343	43	RCL
344	33	33
345	95	=
346	42	STD
347	34	34
348	87	IFF
349	05	05
350	03	03
351	69	69
352	43	RCL
353	20	20
354	99	PRT
355	43	RCL
356	21	21
357	99	PRT
358	43	RCL
359	22	22
360	99	PRT
361	58	FIX
362	02	02
363	43	RCL
364	36	36
365	99	PRT
366	43	RCL
367	34	34
368	99	PRT
369	65	×
370	43	RCL
371	28	28
372	55	÷
373	43	RCL
374	14	14
375	55	÷
376	43	RCL
377	00	00
378	95	=
379	87	IFF
380	05	05
381	03	03
382	84	84
383	99	PRT
384	65	×
385	43	RCL
386	29	29
387	65	×
388	43	RCL
389	17	17
390	95	=
391	49	PRD
392	33	33
393	03	3
394	00	0
395	00	0
396	65	×
397	43	RCL
398	16	16
399	95	=
400	42	STD
401	34	34

Table 3. Continued

402	43	RCL
403	33	33
404	87	IFF
405	05	05
406	04	04
407	09	09
408	99	PRT
409	00	0
410	42	STO
411	36	36
412	42	STO
413	37	37
414	42	STO
415	38	38
416	71	SBR
417	69	OP
418	29	CP
419	67	EQ
420	05	05
421	11	11
422	71	SBR
423	00	00
424	24	24
425	77	GE
426	04	04
427	35	35
428	71	SBR
429	69	OP
430	42	STO
431	36	36
432	61	GTO
433	05	05
434	11	11
435	71	SBR
436	89	π
437	77	GE
438	04	04
439	65	65
440	43	RCL
441	26	26
442	71	SBR
443	55	÷
444	77	GE
445	04	04
446	58	58
447	94	+/-
448	42	STO
449	36	36
450	71	SBR
451	00	00
452	24	24
453	42	STO
454	37	37
455	61	GTO
456	05	05
457	11	11
458	71	SBR
459	69	OP
460	42	STO
461	37	37
462	61	GTO
463	05	05
464	11	11
465	43	RCL
466	26	26
467	71	SBR
468	55	÷
469	77	GE
470	04	04
471	88	88
472	94	+/-
473	42	STO
474	36	36
475	43	RCL
476	34	34
477	71	SBR
478	55	÷
479	42	STO
480	37	37
481	71	SBR
482	89	π
483	42	STO
484	38	38
485	61	GTO
486	05	05
487	11	11
488	43	RCL
489	26	26
490	75	-
491	43	RCL
492	34	34
493	95	=
494	77	GE
495	05	05
496	07	07
497	94	+/-
498	42	STO
499	37	37
500	71	SBR
501	89	π
502	42	STO
503	38	38

Table 3. Continued

504	61	GTO	554	65	×
505	05	05	555	93	.
506	11	11	556	00	0
507	71	SBR	557	00	0
508	69	OP	558	06	6
509	42	STO	559	05	5
510	38	38	560	06	6
511	93	.	561	65	×
512	00	0	562	43	RCL
513	03	3	563	29	29
514	04	4	564	95	=
515	03	3	565	42	STO
516	85	+	566	34	34
517	43	RCL	567	87	IFF
518	27	27	568	05	05
519	95	=	569	06	06
520	65	×	570	07	07
521	43	RCL	571	55	÷
522	36	36	572	43	RCL
523	85	+	573	17	17
524	53	(	574	55	÷
525	93	.	575	43	RCL
526	00	0	576	39	39
527	02	2	577	55	÷
528	06	6	578	43	RCL
529	09	9	579	29	29
530	85	+	580	95	=
531	43	RCL	581	99	PRT
532	27	27	582	43	RCL
533	54	)	583	34	34
534	65	×	584	99	PRT
535	43	RCL	585	85	+
536	37	37	586	43	RCL
537	85	+	587	33	33
538	53	(	588	95	=
539	93	.	589	99	PRT
540	00	0	590	71	SBR
541	02	2	591	06	06
542	01	1	592	11	11
543	01	1	593	99	PRT
544	85	+	594	42	STO
545	43	RCL	595	35	35
546	27	27	596	98	ADV
547	54	)	597	00	0
548	65	×	598	42	STO
549	43	RCL	599	33	33
550	38	38	600	22	INV
551	85	+	601	58	FIX
552	43	RCL	602	86	STF
553	16	16	603	05	05

Table 3. Continued

604	61	GTO
605	01	01
606	46	46
607	44	SUM
608	33	33
609	43	RCL
610	33	33
611	55	÷
612	43	RCL
613	25	25
614	55	÷
615	43	RCL
616	29	29
617	55	÷
618	43	RCL
619	17	17
620	95	=
621	42	STO
622	33	33
623	92	RTN

Table 4. System Information (Refer to Nomenclature List for Designations)

Designations	Value	Data Registers	Units
H_V	150,000	00	Btu/gal
H_S-H_E	435	01	Btu/lb
H_S-H_H	100	02	Btu/lb
H_S-H_L	205	03	Btu/lb
H_E-H_C	860	04	Btu/lb
E_{3T}	0.70	05	%
E_{4T}	0.68	06	%
E_{5T}	0.72	07	%
M_{3M}	2,000	08	lb/hr
M_{4M}	2,300	09	lb/hr
M_{5M}	5,000	10	lb/hr
W_{3M}	1,500	11	kW
W_{4M}	2,000	12	kW
W_{5M}	1,500	13	kW
E_B	0.72	14	%
	3,413	15	conversion factor
D_U	12,654	16	kW
	0.01	17	factor

Table 5. User Instructions

Step	Procedure	Enter	Press		Display
1	Turn on the TI-59 calculator and printer				0
2	Insert magnetic card/sides after pressing:		CLR		1.,2.,3.,4.
3	Enter W_3	W_3	A		ΔW_3
4	Enter W_4	W_4	B		ΔW_4
5	Enter W_5	W_5	C		ΔW_5
6	Enter M_H	M_H	D		M_H
7	Enter M_L	M_L	E		M_L
8	Enter D	D	2nd	A	D
9	Enter K_1	K_1	2nd	B	K_1
10	Enter F_A	F_A	2nd	C	F_A
11	Enter P_F	P_F	2nd	D	P_F
12	Enter T	T	2nd	E	T
13	Start to run the program		RST	R/S	"C"

Table 6. Sample Input/Output Printout

Parameters	Input
W_3 (A)	3,500
W_4 (B)	4,000
W_5 (C)	5,000
M_H (D)	81,300
M_L (E)	21,600
D (A')	16,500
K_1 (B')	100,000
F_A (C')	0.0024
P_F (D')	58
T (E')	8
	First Output
W_3	3,500
W_4	4,000
W_5	5,000
M_C	110,999.68
T_{HR}	12,504.21
C_{US}	6.72
C_{TS}	6,715.22
C_{UP}	5.01
C_{TP}	1,601.68
C_T	8,316.90
C_U	6.30
	Final Output
W_3	2,100
W_4	2,400
W_5	3,000
M_C	55,052.22
T_{HR}	11,180.08

continued

Table 6. Continued

Parameters	Final Output
C_{US}	6.00
C_{TS}	3,602.47
C_{UP}	3.85
C_{TP}	2,773.68
C_{T}	6,376.15
C_{U}	4.83

Table 7. Utility Rate Structures and Fuel Prices Used in Figure 6

	Curve #1	Curve #2	Curve #3	Curve #4
	1972	March 1976 Before	March 1976 After	Aug 1979
Demand charge, \$/kW (with discount)	1.65	2.475	4.15	4.72
Energy charge, ¢/kW-hr (subject to 5% discount)				
1st 50,000	1.3	1.95	3.19	3.43
over 50,000 and up to 300 x demand	1.02	1.53	2.50	2.69
over 300 x demand	0.8	1.2	1.96	2.11
fuel price, ¢/gal	10	32	32	58

Date	Input to Computer			Optimum Operation Per Computer				Actual Operation		
	kW Total Demand	200 psi PPH Steam Demand	Fuel Price cents/gallon	kW Self-Generated	Total Self Gen. Cost	Total Utility Cost	Total Cost	200 psi PPH Steam Demand	kW Total Demand	Total Cost
Time From To	kW Peak Demand	5 psi PPH Steam Demand	K_1 Energy Consumed	Heat Rate Btu/kW-hr	Unit Self Gen. Cost	Unit Utility Cost	Unit Cost	5 psi PPH Steam Demand	kW Self-Gen.	Unit Cost

Table 8. User data sheet.

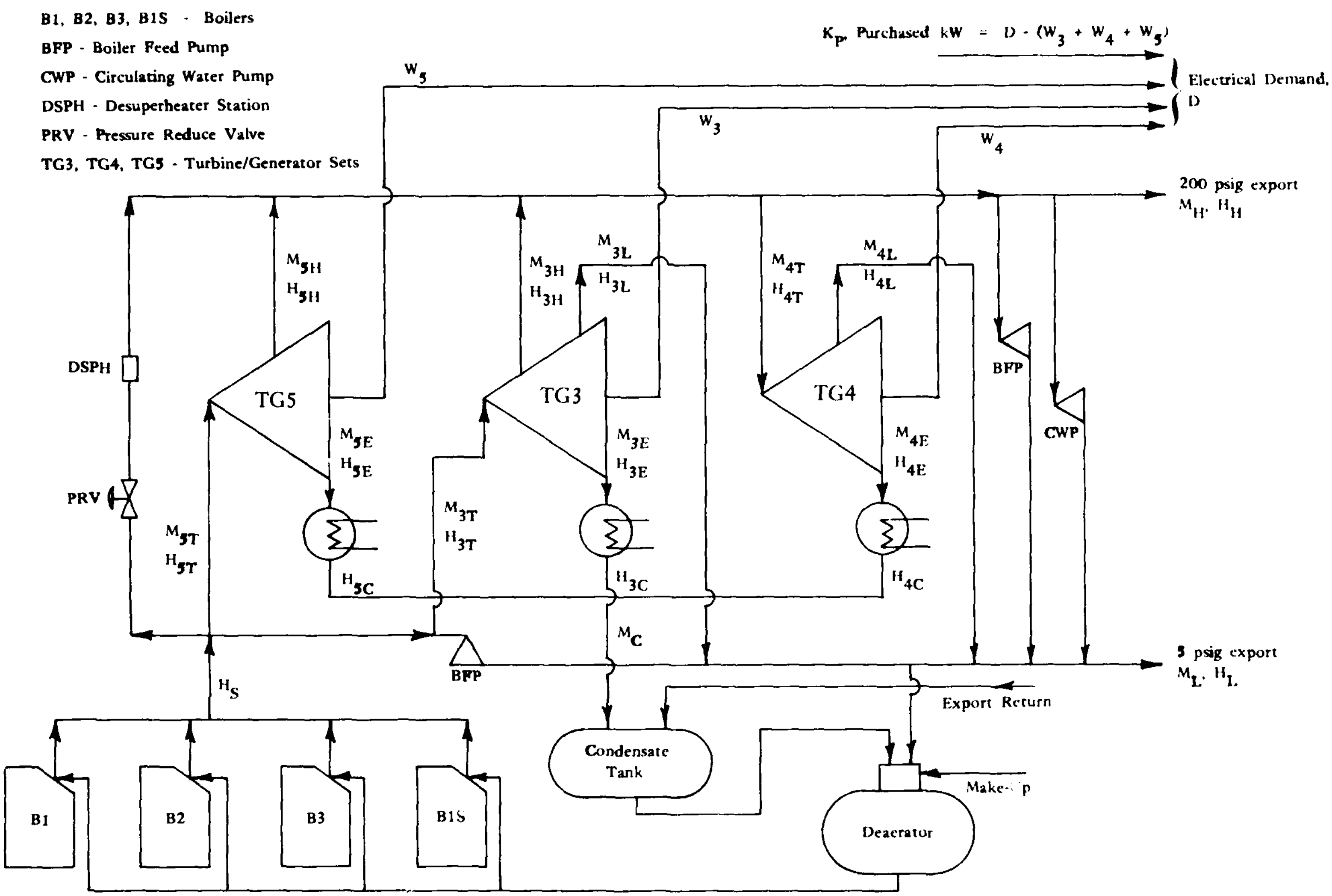


Figure 1. Flow sheet for cogeneration system at SUBASE, New London, Conn.
(Refer to nomenclature list for symbols)

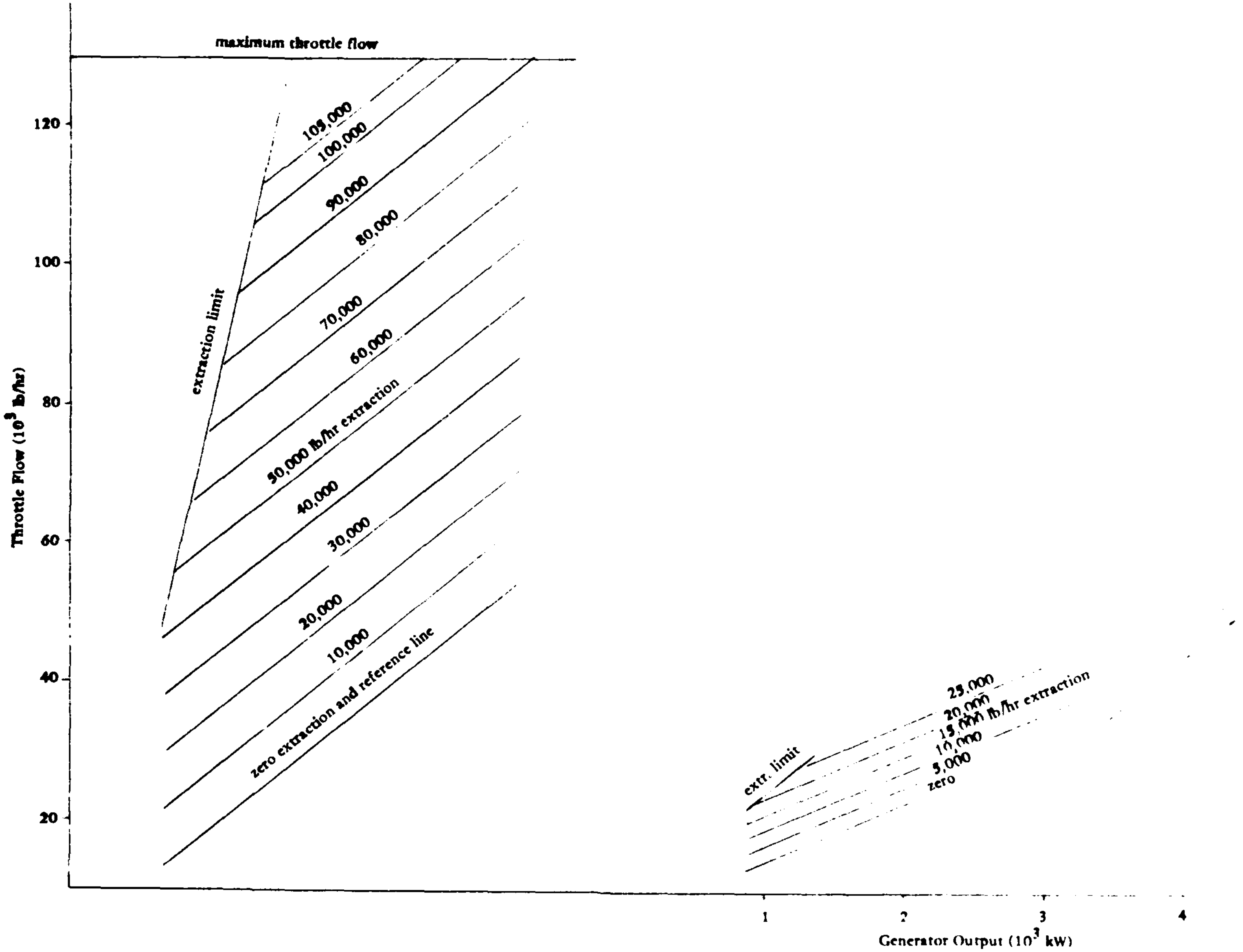


Figure 2. Turbine/generator No. 3 (TG3) performance.

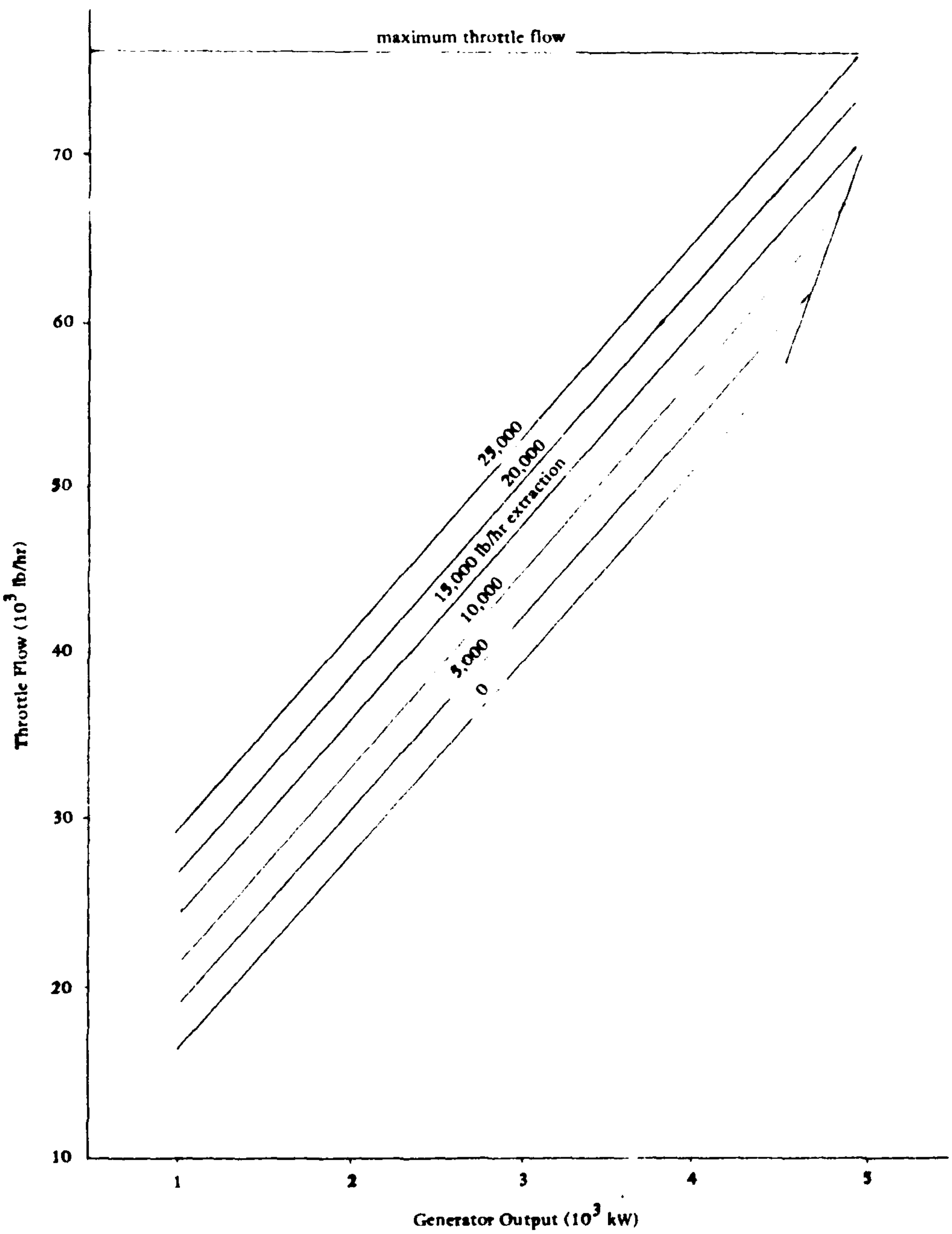


Figure 3. Turbine/generator No. 4 (TG4) performance.

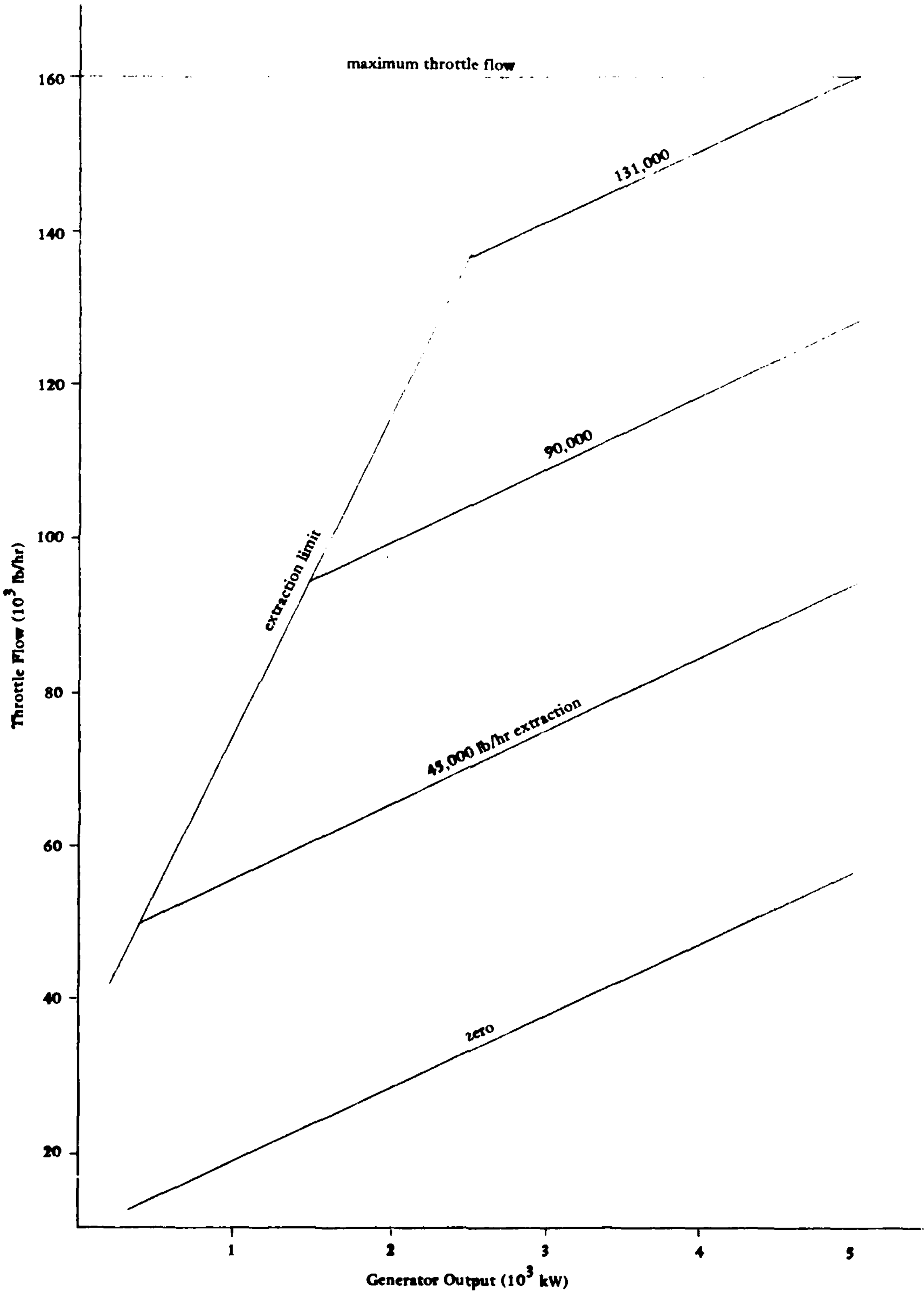


Figure 4. Turbine/generator No. 5 (TG5) performance.

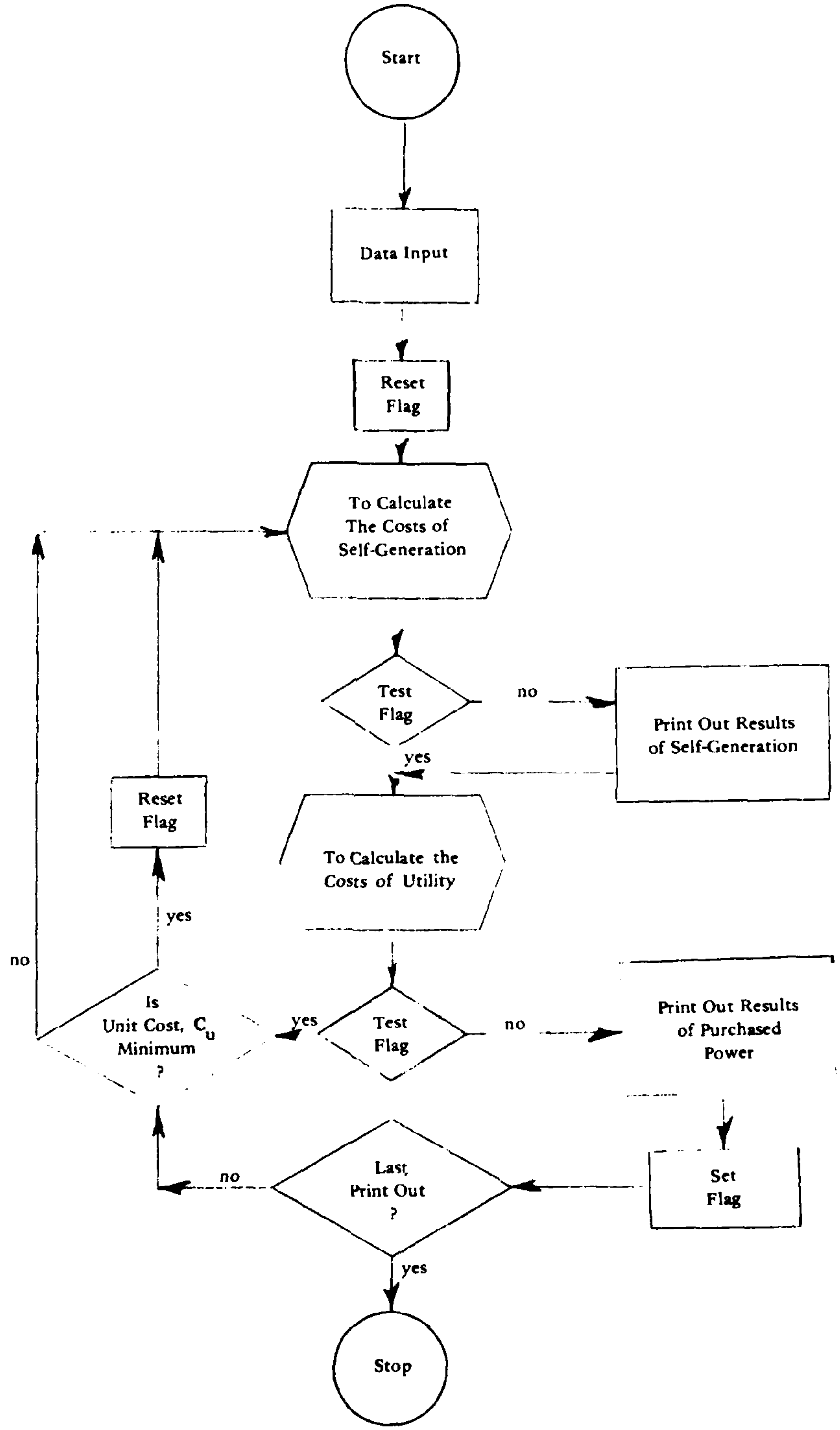


Figure 5. Flow chart of computer program.

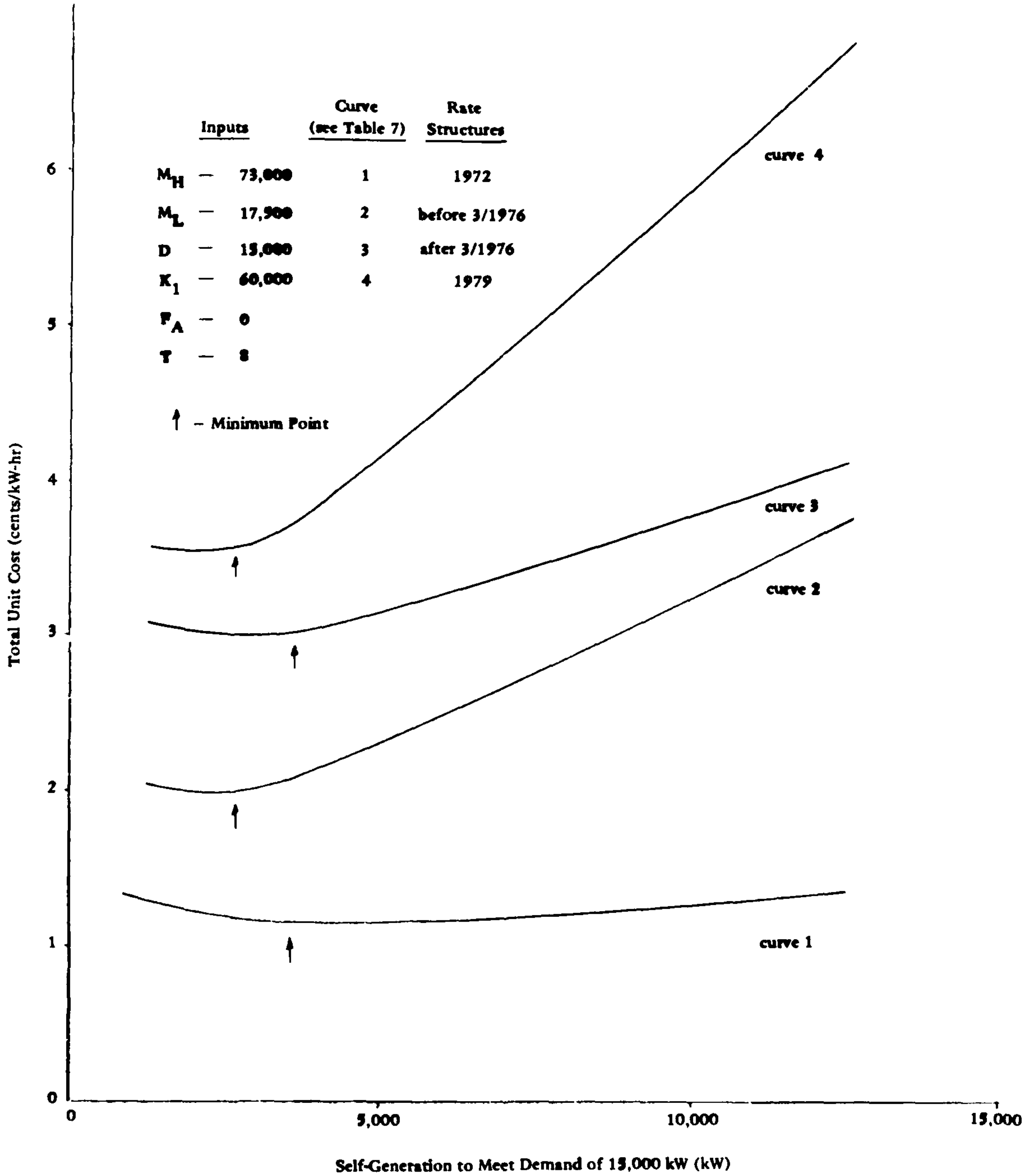


Figure 6. Effect of the rate structure and fuel price on total unit cost.
(Refer to Table 7 for data)

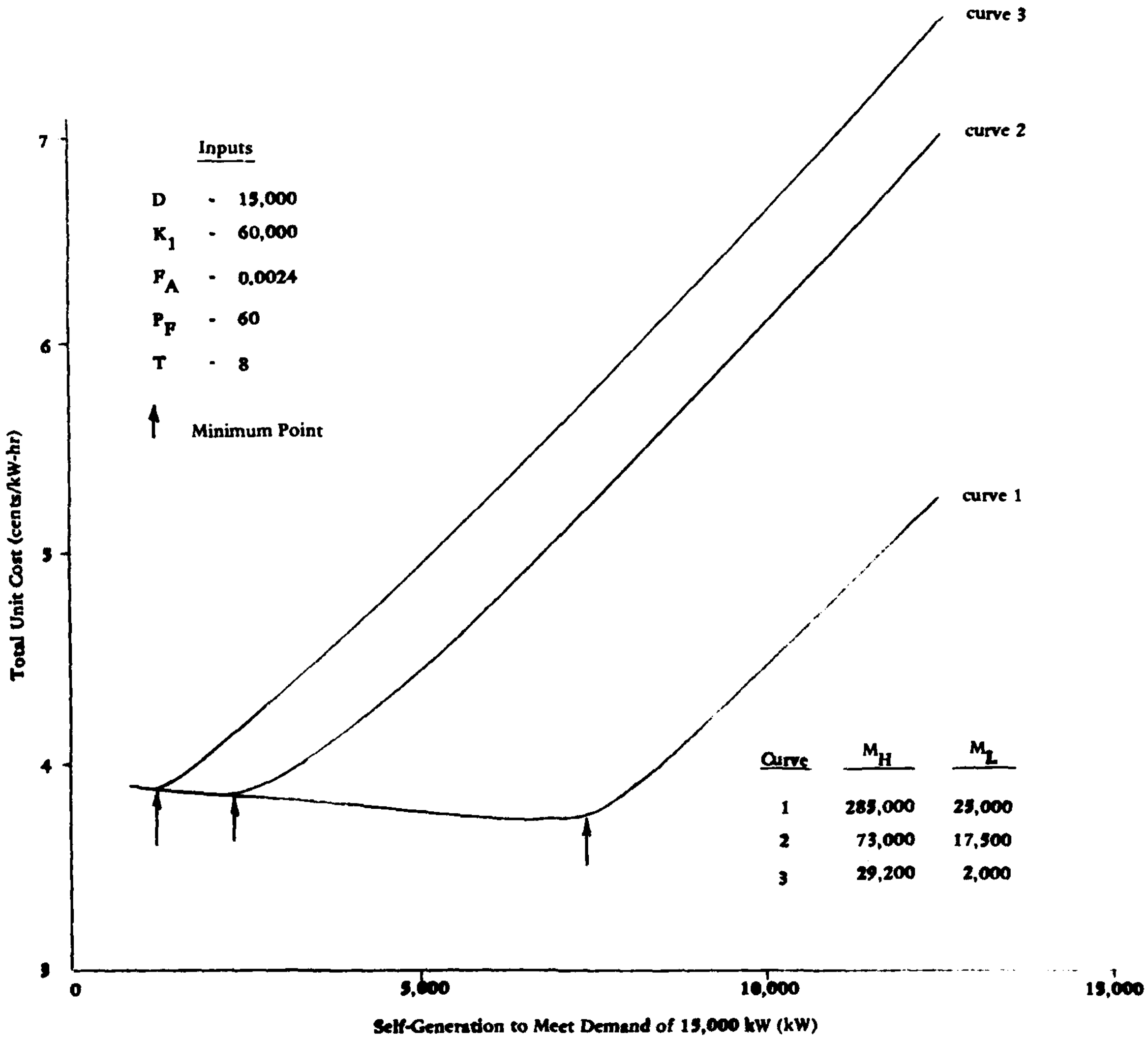


Figure 7. Effect of the steam load on total unit cost.

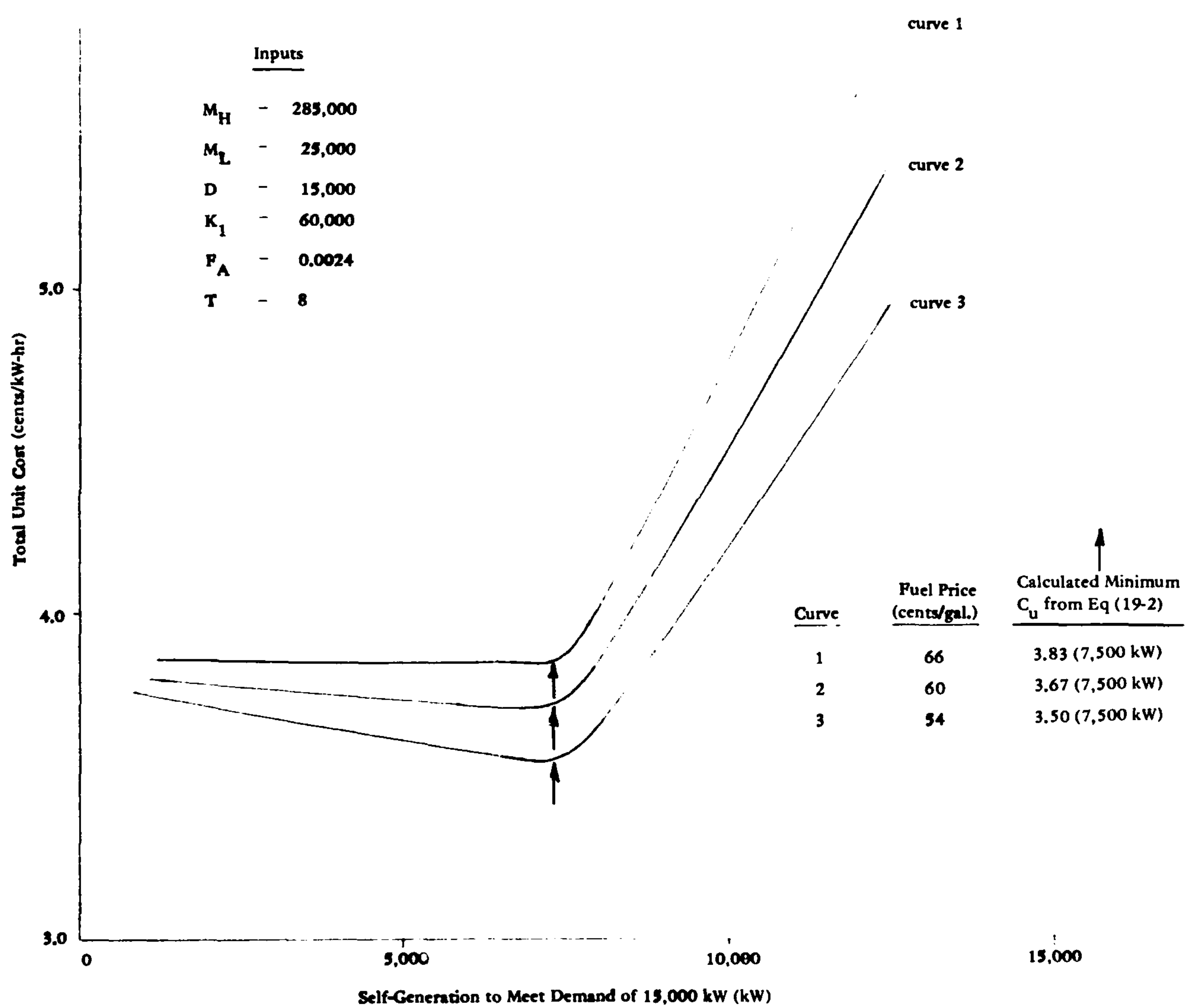


Figure 8. Effect of the fuel price on total unit cost.

NOMENCLATURE LIST

C_T Total cost ($)

C_{TP} Total cost ($) of purchased power

C_{TS} Total cost ($) of self-generated power

C_U Unit cost (¢/kW-hr)

C_{UP} Unit cost (¢/kW-hr) of purchased power

C_{US} Unit cost (¢/kW-hr) of self-generated power

D Electrical demand (kW)

D_U Utility peak demand (kW)

E_B Boiler overall efficiency

E_{iT} Overall efficiency of TGi

F_A Fuel adjustment factor ($/kW-hr)

H_C Enthalpy (Btu/lb) of the mixed condensate

H_E Enthalpy (Btu/lb) of the mixed exhaust steam

H_{iC} Enthalpy (Btu/lb) at condenser outlet of TGi

H_{iE} Enthalpy (Btu/lb) at turbine outlet of TGi

H_H Enthalpy (Btu/lb) of high-pressure (200-psig) export steam

H_{iH} Enthalpy (Btu/lb) at high-pressure (200-psig) extraction point of TGi

H_L Enthalpy (Btu/lb) of low-pressure (5-psig) export steam

H_{iL} Enthalpy (Btu/lb) at low-pressure (5-psig) extraction point of TGi

H_S Enthalpy (Btu/lb) of steam from boilers

H_{iT} Enthalpy (Btu/lb) at turbine throttle of TGi

H_V Heating value of fuel (Btu/gal)

K_P Purchased electrical power (kW)

K_1 Cumulative purchased energy (kW-hr) at the beginning of each run

K_2 Cumulative purchased energy (kW-hr) at the end of each run

M_C Total condensing flow from turbine (lb/hr)

M_H High-pressure (200-psig) export steam (lb/hr)

M_{iE} Flow rate (lb/hr) at turbine outlet of TGi

M_{iH} Flow rate (lb/hr) at high-pressure (200-psig) extraction point of TGi

M_{iL} Flow rate (lb/hr) at low-pressure (5-psig) extraction point of TGi

M_{iM} Minimum required exhaust steam flow (lb/hr) of TGi

M_{iT} Flow rate (lb/hr) at turbine throttle of TGi

M_L Low-pressure (5-psig) export steam (lb/hr)

P_F Fuel price (¢/gal)

T Time period of interest (hr) for each run which may be a period of one shift or less

T_{HR} Heat rate of turbine/generator sets

W_i Electrical output (kW) of TGi

W_{iM} Low limit of electrical output (kW) of TGi

W_T Total self-generated electricity (kW)

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